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RESEARCH MEMORANDUM

ALUMINUM BOROHYDRIDE AS AN IGNITION SOURCE

FOR TURBOJET COMBUSTORS

By David M. Straight, Edward A. Fletcher
and Hampton H. Foster

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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ALUMINUM BOROHYDRIDE AS AN IGNITION SOURCE FOR TURBOJET COMBUSTORS

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SUMMARY

An investigation was conducted to determine the feasibility of using aluminum borohydride as an ignition source in a single tubular turbojet-engine combustor. The combustor-inlet air pressures which limited ignition were determined with a low-volatility fuel for three air-flow rates in the range of engine altitude starting conditions. Ignition limits observed with aluminum borohydride were compared with those obtained with a 0.3-joule spark ignition system and with a 10-joule spark ignition system; these ignition limits were also compared with the steady-state burning limits of the combustor at similar flow rates. Flammability data were also obtained for mixtures of aluminum borohydride with n-pentane in a static test chamber.

For combustor air-flow rates from 1.87 to 6.0 pounds per second per square foot, altitude pressures which limited ignition with aluminum borohydride (single injections of 1 to 2 cc) were about 2 inches of mercury lower than those obtained for a high-energy spark ignition system of 10 joules, 8 sparks per second. At a combustor-inlet pressure of 0.5 atmosphere, the air-velocity ignition limits with aluminum borohydride were about 25 percent greater than those with the 10-joule spark system and about double those with a 0.3-joule spark system. The aluminum borohydride ignition limits occurred at combustor-inlet conditions requiring an estimated spark energy of 100 joules. Static chamber tests indicated that mixtures with n-pentane containing as little as 20 mole percent aluminum borohydride were spontaneously flammable at pressure conditions more severe than those encountered in turbojet-engine operation.

Aluminum borohydride appears to be an excellent ignition source for turbojet combustors. However, there remain problems of storing this chemical and the development of a suitable means of injecting the chemical into the combustor. Further work aimed at the solution of these problems either for aluminum borohydride or another ignitor fluid is considered warranted.

INTRODUCTION

Chemicals that are spontaneously flammable in air and have a high rate of energy release may offer a relatively simple source of ignition

for turbojet combustors, particularly at high altitude engine wind-
milling conditions where ignition is most difficult (ref. 1). According-
ly, a program was initiated at the NACA Lewis laboratory to study the
possibility of using a spontaneously flammable chemical as an ignition
source and to evaluate some of the problems associated with its use.
Aluminum borohydride was selected for this preliminary study because it
has many of the required physical properties and is one of the most
highly flammable substances known.

The combustor-inlet air pressures which limit burning and those
which limit ignition were determined for three air-flow rates (in the
range of altitude engine windmilling conditions) for a low-volatility
fuel. The combustor-inlet air and fuel temperature was held constant at
10° F. Data were also obtained at a low (-46° F) combustor-inlet air
and fuel temperature for one air-flow rate. The combustor ignition lim-
its obtained with aluminum borohydride in specially developed injectors
are compared with those obtained with a spark ignition system at energy
levels of 0.3 and 10 joules.

Problems associated with the use of aluminum borohydride for igni-
tion in aircraft are discussed. A detailed description of its properties
and results of static chamber tests to determine the effect of diluting
aluminum borohydride with n-pentane on flammability in dry air are in-
cluded in this investigation.

APPARATUS AND PROCEDURE

Combustor

A single tubular J33 turbojet-engine combustor (fig. 1) was installed
in a direct-connect duct test facility which supplied the desired altitude
inlet and exhaust conditions. The test facility and instrumentation for
indicating combustor-inlet and -outlet air total pressures, air and fuel
temperatures, and air and fuel flow rates are described in detail in ref-
erence 2. A large (3 by 11.5 in.) transparent plastic window in the outer
shell of the combustor permitted visual observation of the flame. A 10.5
gallon-per-hour, fixed-area fuel nozzle having an 80° spray-cone angle
was used in this investigation. Inasmuch as the fuel passed through a
copper cooling coil (50 ft long and 3/8 in. outside diam.) immediately
before entering the nozzle (fig. 1), the fuel temperature was very near
that of the inlet air. The low-volatility jet-type fuel used was ob-
tained by removing volatile components from MIL-F-5624A stock to adjust
the Reid vapor pressure to a nominal 1 pound per square inch. An analy-
sis of the fuel is given in table I.

The aluminum borohydride was introduced into the combustor from in-
jectors designed to fit into the spark plug hole (fig. 1). The injector
tip was flush with the inside surface of the combustor liner in order to
minimize heating of the unused chemical.

Injector Design and Operation

Glass capsules. - A technique which employed glass capsules was used in early studies to inject aluminum borohydride into the combustor. The apparatus for holding and breaking the glass capsules during the ignition trials is shown in figure 2. A solenoid-operated trigger arm broke the sealed tip from the capillary tube allowing the contents of the capsule to be injected into the combustor. Precision-bore capillary tubing was used in an attempt to control the chemical flow rate. The capillary section was notched 3/4 inch from the main body of the capsule to provide a reproducible breaking point. Standard vacuum line procedure was used in filling the glass capsules. Aluminum borohydride was measured as a liquid in a calibrated tube and was then transferred to the capsule. Sufficient propane was condensed on top of the borohydride by cooling with a liquid nitrogen bath to bring the total propane pressure (at room temperature) up to 15 pounds per square inch gage; the capsule was sealed under vacuum.

The use of glass capsules was found to be unsatisfactory because oxides, formed by the burning liquid, partially or completely plugged the capillary tubing. Several runs were made injecting the chemical into room air through capillary tubes of 0.01, 0.02, and 0.04 inch diameters in an attempt to find a size that would give uniform results. None of these gave satisfactory reproducibility of injection time or appearance of flame because of partial or complete plugging.

Valve-type injector. - The valve-type injector shown in figure 3 was used to obtain the ignition data presented herein. This injector contained a spring-loaded valve, the stem of which extended through the injection valve orifice (0.032 in. diam.). Thus, when the valve was closed after an ignition trial, oxides formed in the orifice were expelled. The injector valve was opened manually by a remote control mechanism. The filling chamber of the injector was designed so that 10 cubic centimeters of aluminum borohydride could be conveniently loaded; however, the quantity of the chemical injected during each ignition trial varied with the amount the valve was opened and the length of time it was held open. Prior to being loaded with aluminum borohydride, the injector was connected to a glass vacuum line through a glass-to-metal spherical joint and evacuated. The desired quantity of the chemical was then condensed into the condensing chamber (fig. 3) by cooling in liquid nitrogen. With the liquid nitrogen bath still in place, oil-pumped nitrogen was admitted into the injector to a pressure of 0.5 atmosphere and the filling valve closed. The total pressure inside the injector (at room temperature) was about 7 pounds per square inch gage. This pressure was held constant during the combustor test period by connecting the injector (through a reducing valve) to a cylinder of oil-pumped nitrogen.

Aluminum borohydride. - A description of the chemical and physical properties of aluminum borohydride is presented in the appendix.

Test Procedure

Burning limits. - The minimum combustor-inlet air pressures at which
burning could be maintained were determined for three air flows (1.87,
3.75, and 6.0 lb/(sec)(sq ft) based on a combustor maximum cross-
sectional area of 0.267 sq ft) at a constant air and fuel temperature of
10° F. The burning limit was determined for a reduced inlet air and fuel
temperature (-46° F) at one air-flow rate (3.75 lb/(sec)(sq ft)). A
description of the method used to determine the combustor burning limits
is presented in reference 3.

Ignition limits with electric spark. - The minimum combustor-inlet
air pressure at which ignition could be obtained with a spark energy of
10 joules (at 8 sparks/sec) was obtained for the aforementioned combustor-
inlet conditions. A detailed description of the ignition system and pro-
cedure used is presented in reference 4.

Ignition limits with aluminum borohydride. - After the desired
combustor-inlet conditions were established within the combustor, fuel
was admitted at a rate previously determined to be optimum for ignition
(fuel-air ratio, approximately 0.015). The aluminum borohydride was then
injected into the fuel-air mixture. Ignition was indicated by a temper-
ature rise and by observation of flame through the window in the combus-
tor. Inasmuch as aluminum borohydride ignites spontaneously in air, flame
was always visible, at least momentarily, whether or not the combustor
was successfully ignited. The criterion for satisfactory ignition was
that the flame fill the combustor and continue burning after the source
of ignition had been shut off. One injection of the chemical (approxi-
mately 2 cc) was usually sufficient for ignition if the combustor-inlet
air conditions were within the ignition limits.

RESULTS AND DISCUSSION

The minimum combustor-inlet pressures at which ignition could be ob-
tained both with aluminum borohydride and with an electric spark system
over a range of air-flow rates are shown in figure 4. The 0.3-joule, 8
sparks per second ignition limit curve shown in figure 4 was obtained in
a previous investigation (ref. 3) and represents the energy supplied by
one current turbojet engine ignition system at 20 sparks per second. A
spark energy of 10 joules represents the probable upper energy limit for
proposed spark ignition systems; data obtained with this spark energy at
8 sparks per second are shown in figure 4. Data points shown for the
chemical ignition should be considered approximate limits inasmuch as the
number of runs made was insufficient to permit a complete statistical
analysis; the data are listed in table II. The limiting pressures for
ignition with aluminum borohydride are 1.5 to 2.5 inches of mercury lower
than those with 10-joule sparks, and are 5 to 8 inches of mercury lower

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than those with 0.3-joule sparks. At a combustor-inlet pressure of 0.5
atmosphere, the air-velocity ignition limits with aluminum borohydride
were about 25 percent greater than those with the 10-joule spark system
and about double those with a 0.3-joule spark system. As shown in fig-
ure 4, an increase in air-flow rate from 1.87 to 6.0 pounds per second
per square foot increased the minimum pressures for ignition by about 8
inches of mercury with either the 10-joule or the chemical ignition
source. A decrease in combustor-inlet air and fuel temperature from 10°
to -46° F increased the limiting pressure for burning and for ignition
by about 2 inches of mercury. The actual quantities of aluminum boro-
hydride and the duration of the injection are not known because of meter-
ing difficulties encountered. In most of the runs, the injector was
loaded with 5 cubic centimeters of the chemical. Two or three ignition
trials usually could be obtained with each loading when very short in-
jection periods were used (less than 1 sec). There was evidence that not
all of the chemical could be expelled from the injector. This was attri-
buted to absorption of some of the liquid by a polymer (see appendix)
formed inside the injector during previous ignition trials.

Increasing the period over which a given quantity of chemical is in-
troduced may possibly lower the ignition limit below the values shown in
figure 4 by permitting an approach to a steady-state burning condition
during the injection of aluminum borohydride. In addition, a lower in-
jection rate may reduce the quantity of aluminum borohydride required for
each ignition. Satisfactory ignitions were obtained (at an air flow of
1.87 lb/sec/sq ft and an inlet pressure of 10 in. Hg abs) with as little
as 0.5 cubic centimeter of aluminum borohydride, the minimum quantity
injected.

An estimate (fig. 5) of the spark energy required for ignition at
combustor-inlet conditions which limited ignition with aluminum borohy-
dride was obtained from an empirical relation (ref. 4) between the mini-
mum spark energy for ignition and $V/\sqrt{P}$ (where V is the reference
velocity in ft/sec based on inlet air density and maximum combustor
cross-sectional area, and P is the inlet-air total pressure in in. Hg
abs). The data points shown in figure 5 below the 5-joule level are from
reference 4. The $V/\sqrt{P}$ values at the 10-joule level were determined
from the data of figure 4. The range of values of $V/\sqrt{P}$ at which igni-
tion was obtained with aluminum borohydride is also shown in figure 5.
Extrapolation of the curve of figure 5 to the values of $V/\sqrt{P}$ corres-
ponding to the aluminum borohydride ignition limit shows that a spark
energy of approximately 100 joules would be required to achieve ignition
at these severe conditions, if the extrapolation is assumed valid. One-
hundred joules is the energy equivalent of only about 0.003 cubic centi-
meter of aluminum borohydride.

It is anticipated that even better ignition characteristics might
result from the use of aluminum borohydride-hydrocarbon mixtures, since

injector plugging might thus be reduced and the injection interval increased. A study of the flammability of such mixtures with n-pentane (described in the appendix) revealed that mixtures containing as little as 20 mole percent aluminum borohydride were spontaneously flammable in relatively dry air at room temperature at an absolute pressure of 1.0 inch of mercury, a pressure condition more severe than any current turbojet operating condition.

CONCLUDING REMARKS

A comparison of the ignition limits obtained in a single tubular combustor with aluminum borohydride and with a spark ignition system at 0.3- and 10-joule energy levels showed that the combustor-inlet air pressures which limited ignition were about 2 inches of mercury lower for the aluminum borohydride than for the high-energy, 10-joule spark system. At a combustor-inlet pressure of 0.5 atmosphere, the air-velocity ignition limits with aluminum borohydride were about 25 percent greater than those with the 10-joule spark system and about double those with a 0.3-joule spark system. A decrease in inlet-air and fuel temperature from 10° to -46° F raised the pressures limiting ignition by about 2 inches of mercury with either the high-energy or the chemical ignition system. Mixtures of n-pentane and as little as 20 mole percent aluminum borohydride were spontaneously flammable in a static test chamber filled with relatively dry air at room temperature at an absolute pressure of 1.0 inch of mercury.

Although these data show that aluminum borohydride is potentially an excellent source of ignition for turbojet combustors, practical means of storing, transporting, and injecting the chemical must be devised before it can be used in aircraft. The potential fire hazard and storage problem due to pressure resulting from vaporization and decomposition of aluminum borohydride can conceivably be minimized by storage container design and location on the aircraft. Metering may possibly be facilitated by using positive displacement injection or by mixing the chemical with hydrocarbons. Further study of the problems associated with the use of aluminum borohydride is warranted in view of the outstanding ignition characteristics obtainable. Other spontaneously flammable substances may not present some of these difficulties and therefore also warrant study.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, July 20, 1953

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APPENDIX - ALUMINUM BOROHYDRIDE

Physical Properties

Aluminum borohydride is a colorless liquid that is soluble in both aromatic and aliphatic hydrocarbons in all proportions. Its physical properties are summarized in the following table:

Property	Value	Temperature dependence[a]	Reference
Melting point, $^{\circ}C$	-64.5		5
Normal boiling point, $^{\circ}C$	44.5		5
Vapor pressure at 20° C, mm Hg	295	$\log p = 7.808 - 1565/T$	5
Density at 20° C, g/cc	0.554	$\rho = 0.7866 - 0.000793T$	6
Viscosity at 20° C, centipoises	0.216	$\mu = 23 \times 10^{-3}\, \rho^{\frac{1}{3}}\, e^{1291\rho/T}$	6
Surface tension at 20° C, dynes/cm	15.4	$\gamma = (61.0 - 0.130T)\rho^{\frac{2}{3}}$	6
Heat of combustion, joules/cc (24,800 Btu/lb)	32,000		7
Heat of hydrolysis, joules/cc	4477		7

[a]T is temperature in $^{\circ}K$.

The fluid properties at room temperature are very similar to those of diethyl ether.

Flammability

Aluminum borohydride is one of the most highly flammable substances known; the liquid bursts into flame spontaneously and burns vigorously in air. This property is shown in the sequence of motion-picture frames presented in figure 6. These photographs were taken at the rate of 24 frames per second and depict the flame produced when 0.6 cubic centimeter of aluminum borohydride was injected into atmospheric air through a capillary tube under a pressure differential of 15 pounds per square inch. The capillary tube was 0.75 inch long and had a diameter of 0.04 inch. The interval shown is 0.63 second. The capsules used in the initial ignition experiments presented an additional hazard which was not anticipated. The capsules were usually simply broken in half after an injection to admit air into them. It was observed, however, that each time one of the

fragments was smashed, there was a small explosion even though the sur-
face had been previously exposed to air. This suggests that the mere
absence of flame when equipment which has held aluminum borohydride is
exposed to air is not good evidence of decontamination of that equipment.
Careful washing with alcohol to decompose flammable residues followed
by washing with water is recommended.

Mixtures of aluminum borohydride with n-pentane showed a similar
tendency to flame spontaneously. Static tests were conducted in a trans-
parent plastic chamber (343 cu in.) shown schematically in figure 7. The
chamber was equipped with fittings for holding glass injection capsules
and a hammer for breaking them, a vacuum pump, a barometer, and a means
of introducing -72° F dew point air. Flammability tests were conducted in
the following manner: The chamber was first evacuated to less than 0.004
inch of mercury absolute and dehumidified air was added to a pressure of
1 inch of mercury absolute. The end of the capsule was then broken to
allow the fuel to spray into the chamber propelled by its own vapor pres-
sure. The flames were observed visually. In all the tests the fuel sam-
ple contained 0.033 cubic centimeter of aluminum borohydride (the stoi-
chiometric amount for the air in the chamber) plus sufficient n-pentane
to give mixtures having compositions of 100, 80, 60, 40, and 20 mole per-
cent aluminum borohydride. The n-pentane had been previously dried over
calcium hydride. The fuels were measured as vapors and the capsules were
filled in a conventional high vacuum line.

All the mixtures tested burst into flame immediately on injection
into the static test chamber, although the least concentrated solution
contained only 20 mole percent aluminum borohydride.

Aluminum borohydride vapor explodes violently when exposed to moist
air (ref. 5), but can, under proper conditions, be mixed with dry oxygen
without explosion. However, even dry mixtures of this compound with oxy-
gen will ignite under certain conditions (ref. 8).

Aluminum borohydride reacts instantly and explosively with water and
with reducible substances. These include many materials containing oxy-
gen or halogens.

Storage

Aluminum borohydride does not attack most of the common metals of
construction - steel, brass, copper, aluminum, lead, and nickel. When
stored at room temperature it decomposes slowly to produce hydrogen and
a polymeric substance. The polymer is very soluble in aluminum borohy-
dride and contains aluminum, boron, and hydrogen; its chemical properties
are similar to those of the borohydride (ref. 9). Reference 10 reports
that the initial rate of decomposition was 0.1 percent per day and that

the decomposition rate decreased rapidly with time. Decomposition represents only a minor problem insofar as loss of borohydride is concerned; however, the decomposition might present a rather serious problem insofar as storage is concerned. Hydrogen is produced in relatively large volumes and the pressure buildup in closed containers might conceivably become quite large. Decomposition at room temperature, however, ultimately becomes negligibly slow. At this laboratory, the hydrogen given off from a 10-cubic-centimeter sample of aluminum borohydride was removed through a vacuum pump at intervals over a period of 3 months. The sample was then stored in a glass bulb for 2 years; during this time the pressure rise was less than 1 atmosphere. In reference 9 the retardation of decomposition is attributed to the formation of a nonvolatile decomposition product which acts as an inhibitor to further decomposition. Formation of the inhibitor is greatly accelerated by raising the temperature; thus aluminum borohydride can be stabilized by heating at 40° C for 4 days. If the resulting hydrogen is bled off at intervals during this period, the likelihood of subsequent pressure buildup is minimized. Stabilization will not remain effective if the borohydride is to be stored at temperatures very much above 25° C. In the stabilization process, temperatures higher than 40° C will cause the inhibitor to become ineffective; heating periods longer than 4 days do not improve the results.

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TABLE I. - FUEL ANALYSIS

Fuel property	NACA fuel 50-197 (modified MIL-F-5624A grade JP-3)
A.S.T.M. distillation D86-46, °F Initial boiling point	181
Percentage evaporated	
5	242
10	271
20	300
30	319
40	332
50	351
60	356
70	381
80	403
90	441
Final boiling point	508
Residue, percent	1.2
Loss, percent	0.2
Reid vapor pressure, lb/sq in.	1.0
Hydrogen-carbon ratio	0.170
Heat of combustion, Btu/lb	18,691
Specific gravity	0.780
Freezing point, °F	< -76
Viscosity, centistokes at 100° F	1.05

TABLE II. - IGNITION DATA WITH ALUMINUM BOROHYDRIDE

Run	Combustor air flow, lb/sec/sq ft	Fuel-air ratio	Chemical injector type	Quantity of chemical in injector, cc	Combustor-inlet pressure, in. Hg abs	Combustor-inlet temperature, °F	Observation
1	1.87	0.018	Glass	0.50	14	10	Excellent start
2			Capsule	.50	11		Excellent start
3				.50	10		Excellent start
4	↓	↓	↓	.50	9	↓	No flame - capsule may have plugged
5				1.0	9		Starts but blows out
6	3.75	0.011	Valve	5.0	25	10	Good start
7				----	20		Good start
8				----	15		No flame - apparently no chemical in injector
9				1.0	14.5		Good start
10				----	11.0		No flame - apparently no chemical in injector
11				1.5	14.5		No flame - polymer may be absorbing chemical
12				6.0	14		Good start
13				----	13		Good start
14				----	12		No flame - polymer may be absorbing chemical
15				----	29		No flame - polymer may be absorbing chemical
16				5.0	12		Chemical flame - no burner start
17				----	12		Burner starts but blows out
18	↓	↓	↓	----	12	↓	Small chemical flame - no burner start
19	1.87	0.018	Valve	5	8	10	Good start but blows out
20	↓	↓	↓	----	8	↓	Chemical flame - no burner start
21				----	8		No flame - probably no chemical injection
22	6.0	0.012	Valve	5	16.5	10	No flame - chemical may be absorbed by polymer
23				5	17		Good start
24				----	16		No flame - remaining chemical may be absorbed by polymer
25				5	16.5		Good start
26	↓	↓	↓	----	16	↓	No flame - remaining chemical may be absorbed by polymer
27	3.75	0.011	Valve	5	14.2	-46	Good start - but blows out after few seconds
28				----	16.5		Good start - but blows out after few seconds
29	↓	↓	↓	----	13.5	↓	No flame

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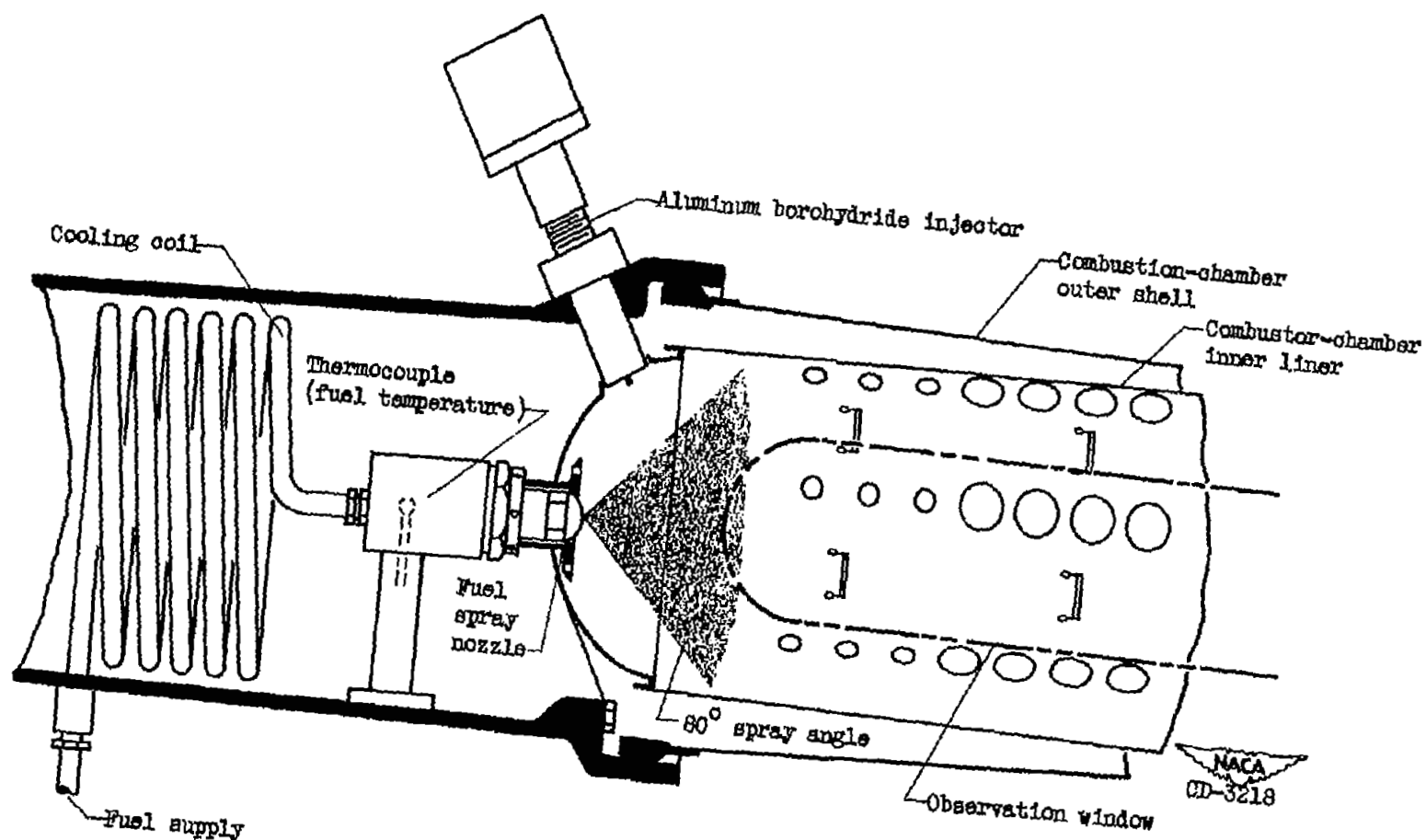
Figure 1. - Diagrammatic cross section of single tubular combustor.

Labels on figure:
- Cooling coil
- Aluminum borohydride injector
- Combustion-chamber outer shell
- Combustor-chamber inner liner
- Thermocouple (fuel temperature)
- Fuel spray nozzle
- 80° spray angle
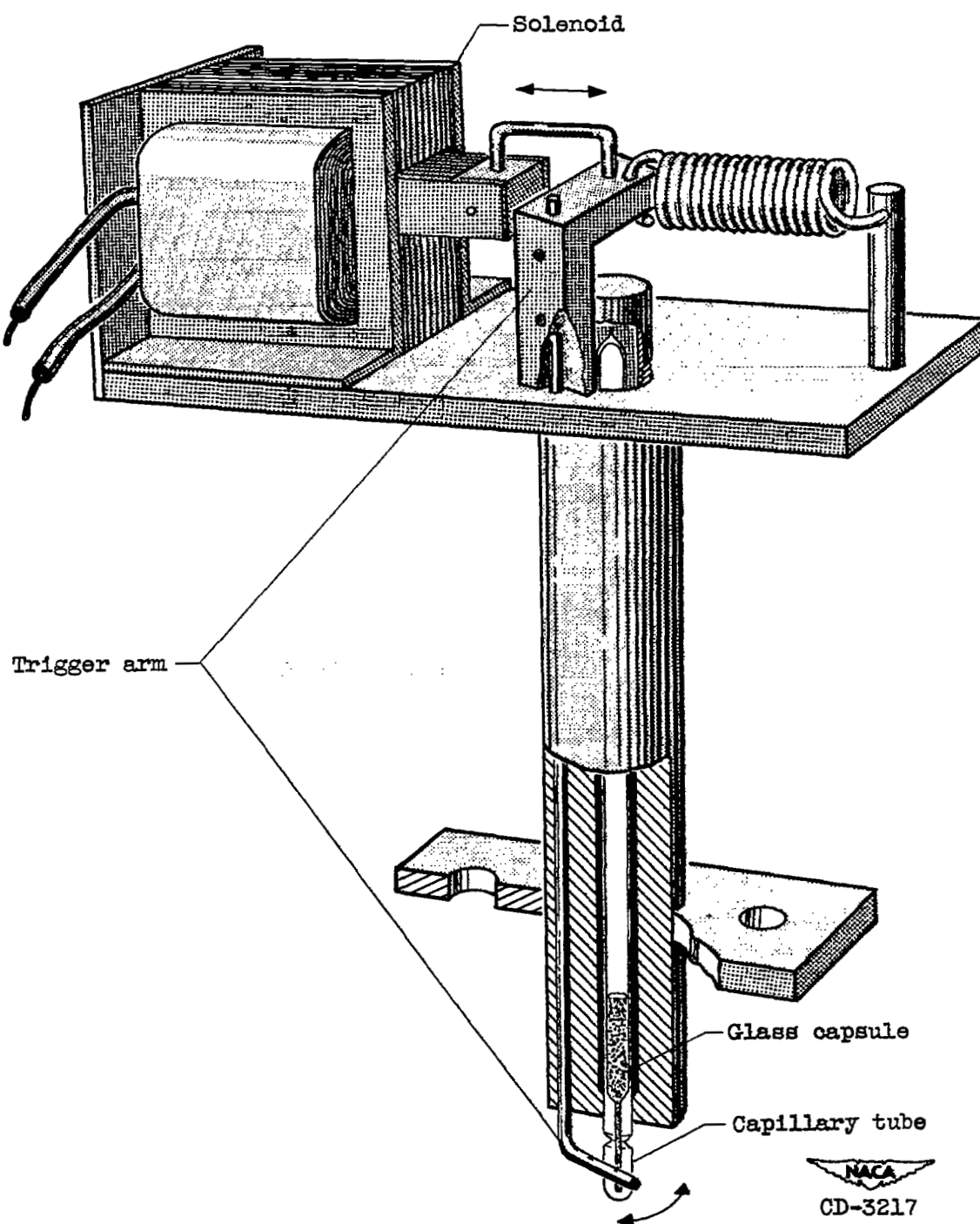- Observation window
- Fuel supply
- NACA CD-3218

Figure 2. - Diagrammatic sketch of injector using pressurized glass capsule with capillary tube for injecting single charges of aluminum borohydride.
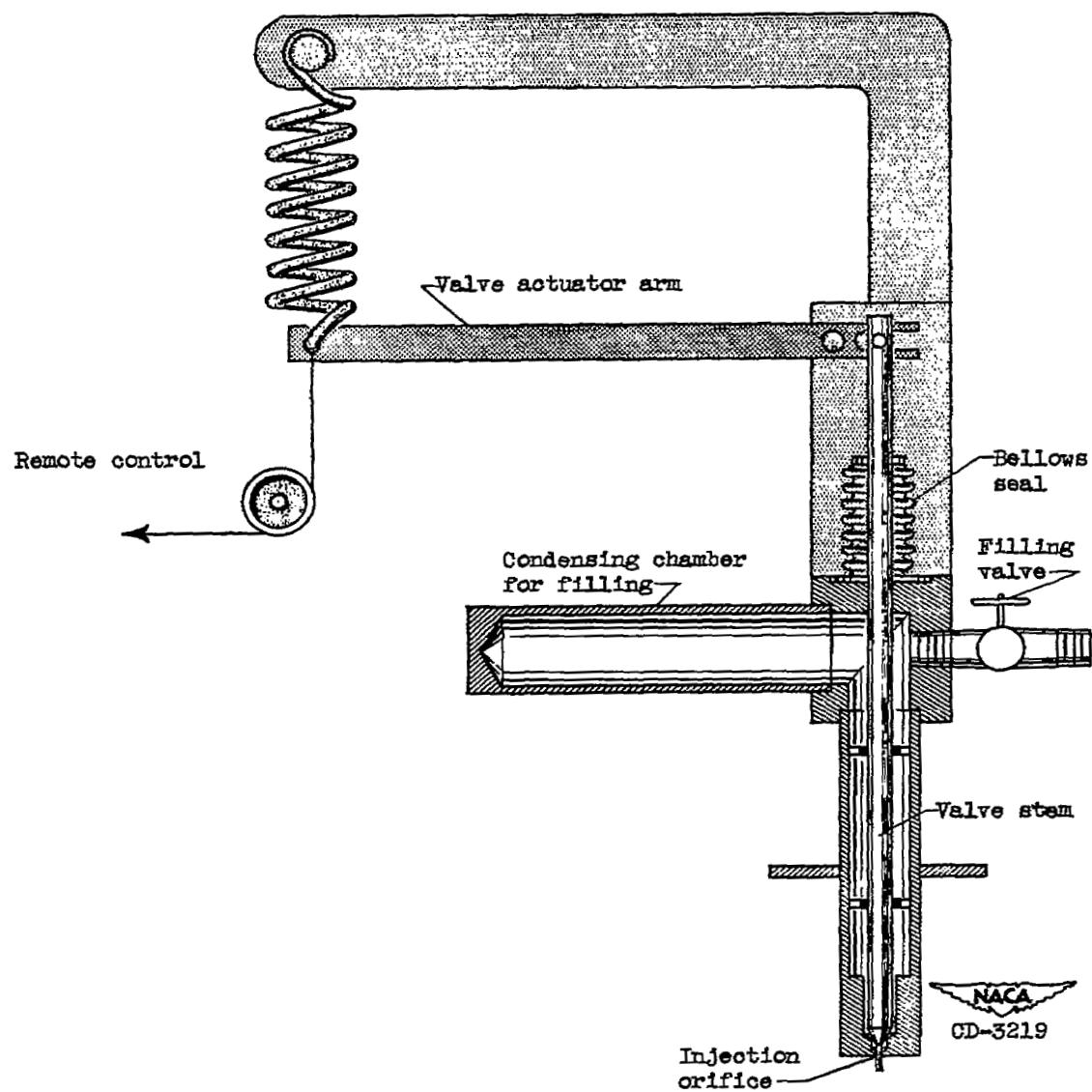
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Valve actuator arm

Remote control

Bellows seal

Condensing chamber for filling

Filling valve

Valve stem

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CD-3219

Injection orifice

Figure 3. - Valve-type aluminum borohydride injector.

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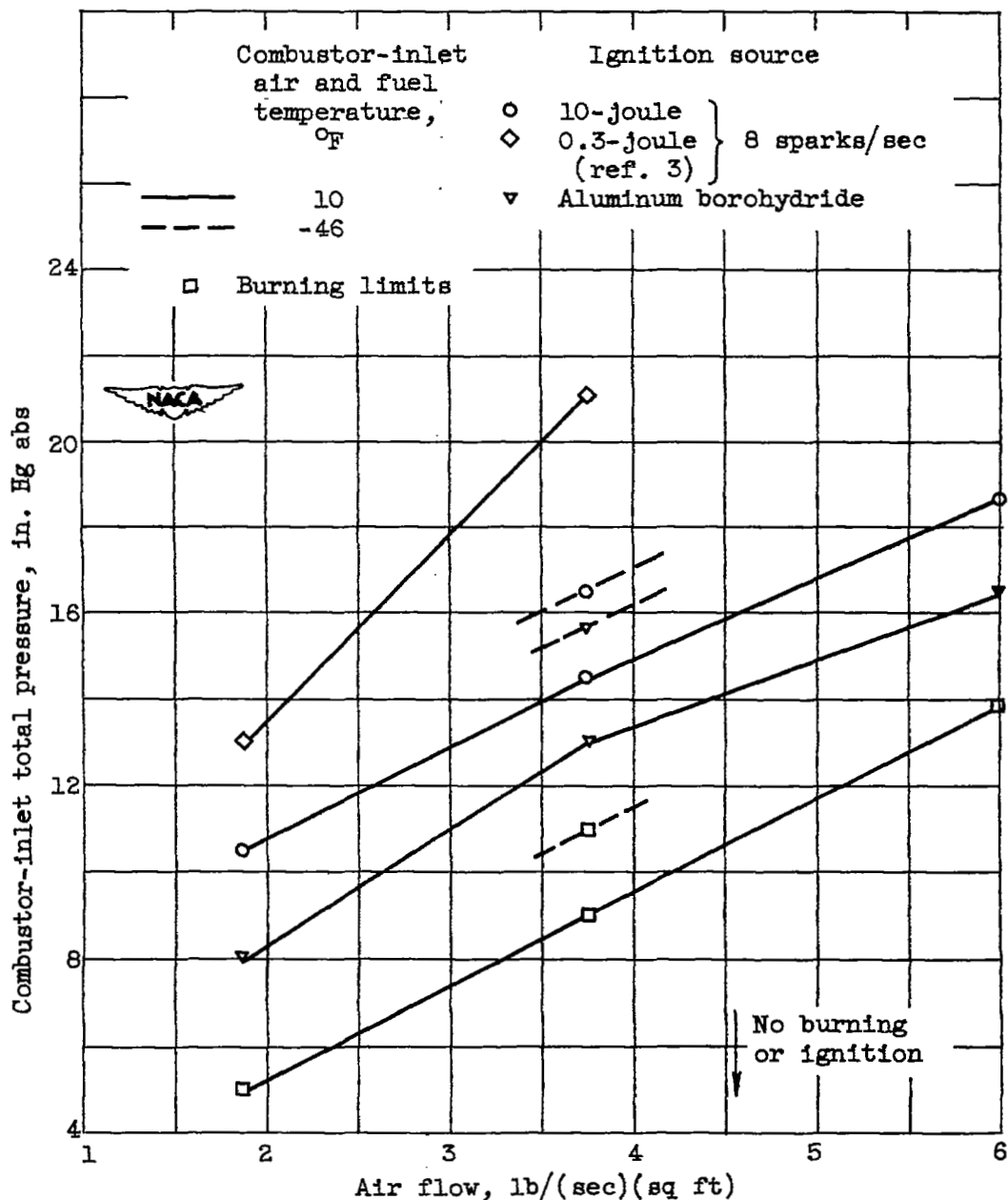
Figure 4. - Comparison of combustor burning limits with combustor
  ignition limits obtained with electric spark and with aluminum
  borohydride as sources of ignition. Fuel, 1-pound Reid vapor
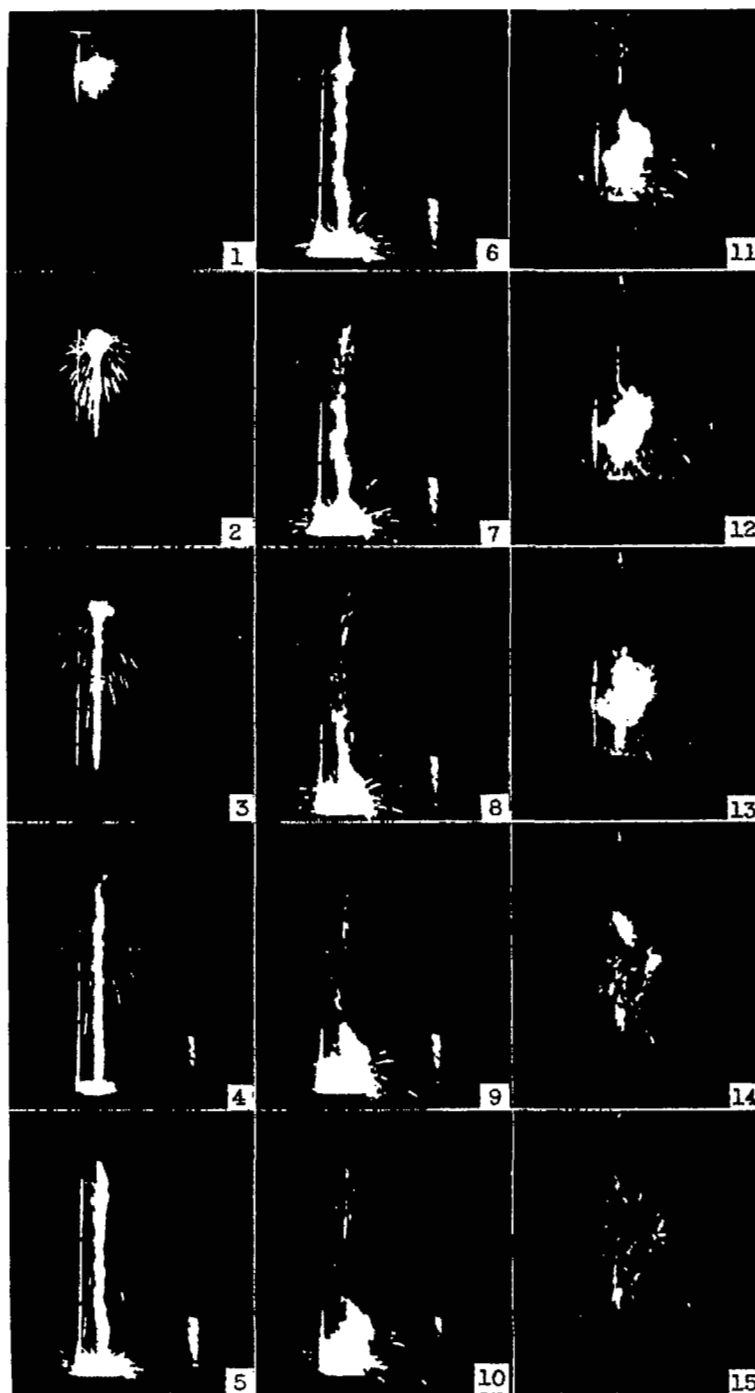 pressure (NACA fuel 50-197); fuel nozzle, 10.5 gallon-per-hour,
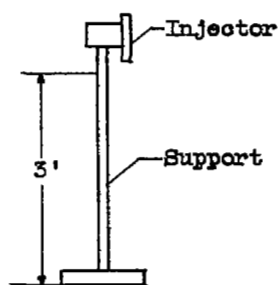 fixed-area; spray-cone angle, 80°.

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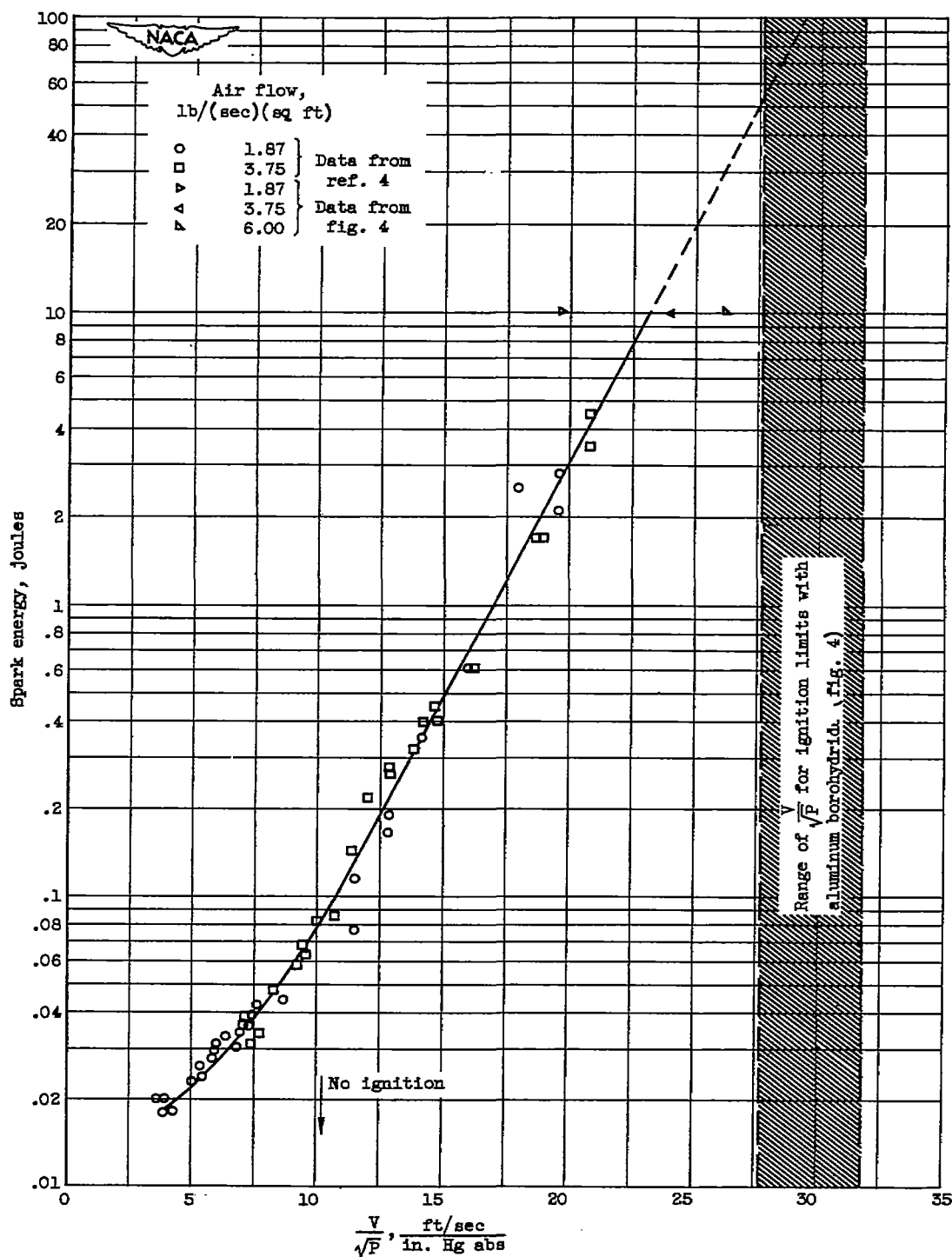
Figure 5. - Minimum spark energy required for ignition as a function of combustor-inlet air pressure and velocity. Combustor-inlet air and fuel temperature, 10° F.

Figure 6. - Photographs of flame produced by 0.6 cubic centimeter of aluminum borohydride injected through capillary tube into air at pressure of 1 atmosphere. Capillary tube, 0.04-inch diameter, 0.75-inch length; initial injection pressure, 15 pounds per square inch.
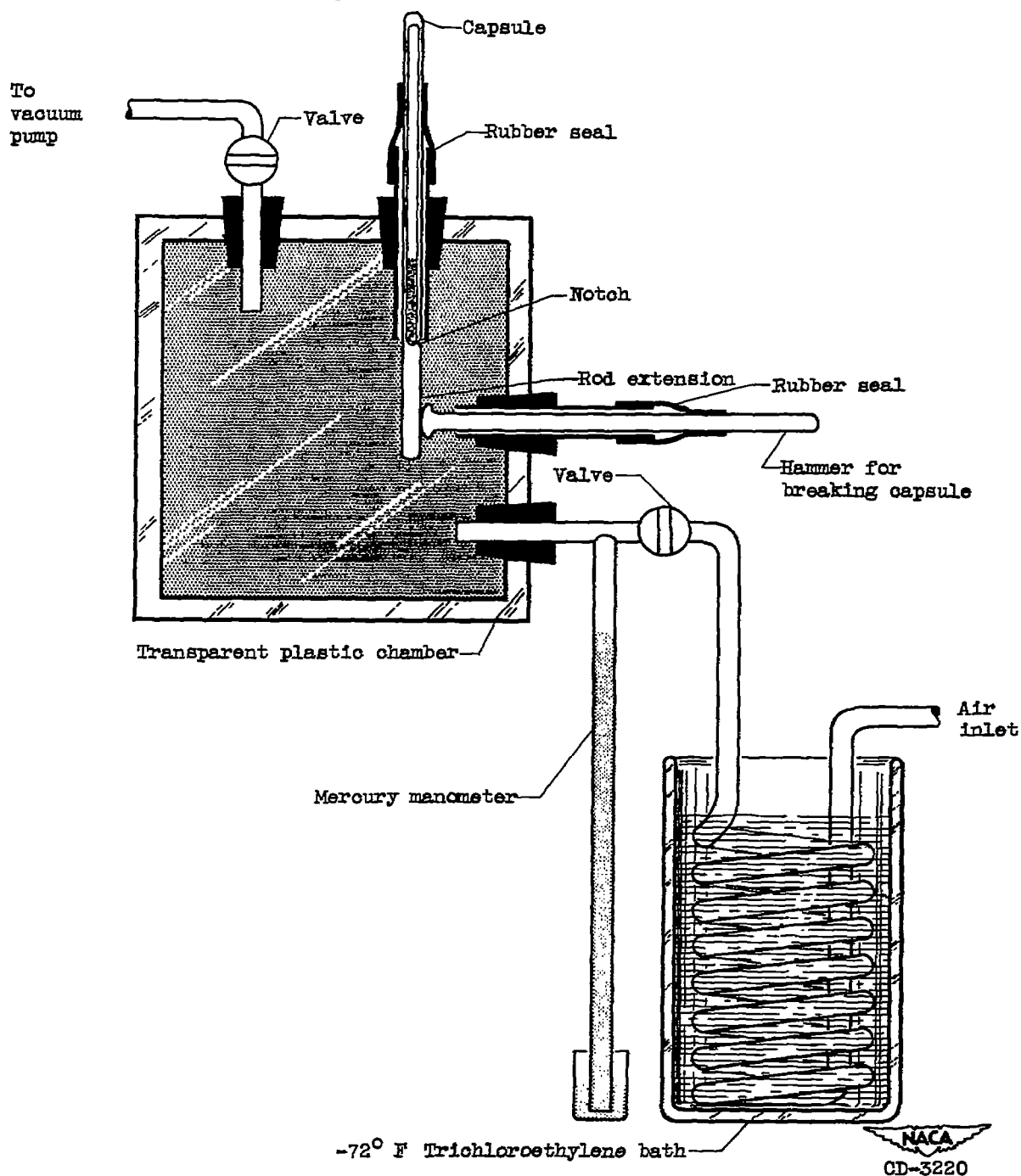
Figure 7. - Schematic diagram of static test chamber used for determining flammability of aluminum borohydride mixtures with n-pentane.